

Power-Cylinder Friction Reduction through Coatings, Surface Finish, and Design

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Project ID #
FT050

Overview

Timeline

- Project start date: Jan 1, 2015
- Project end date: Dec. 31, 2018
- Percent complete – 60%

Budget

- Total project funding
 - DOE share: \$820,000
 - Contractor share: \$250,000
- Funding received in FY 2016: \$207,622
- Funding for FY 2017: \$252,511

Barriers

- Barriers addressed
 - Reduce CO2 emissions
 - Reduce dependency on foreign oil
 - Conserve natural resources (petroleum)

Partners

- Argonne National Laboratory
- Suppliers
 - Comau
 - Gehring
 - Dow Chemical
 - Paramount
 - Mahle
 - KS
 - SwRI

Relevance

- **Overall Objectives**

- Develop and demonstrate friction reduction technologies for light and medium duty vehicles improving 4% fuel efficiency by using
 - High porosity plasma transfer wire arc (PTWA) coatings
 - Low friction ring coatings
 - Low friction piston skirt nano-composite coating
 - Micro-polished crank journals
 - Low friction polyalkylene glycol engine oils

- **Objectives for this period**

- Demonstrate deposition of high porosity plasma transfer wire arc (PTWA) coatings at porosity levels
 - 0-2%
 - 3-5%
 - 6-8%
- Demonstrate friction reduction potential of these coatings using bench and components tests
- Demonstrate friction reduction potential of micro-polished crank journals

- **Impact**

- The technologies have the potential to
 - Significantly reduce CO₂ emissions
 - Conserve natural resources (petroleum)
 - Reduce dependency on foreign oil

Approach















- **Technology Development**

- Develop high porosity PTWA coating (supplier collaboration)
 - Identify key coating deposition parameters and define their levels
 - Develop honing and surface finishing conditions
 - Understanding mechanism(s) of porosity generation
- Develop nano-composite coatings for rings and piston skirts
- Identify and develop micro-polishing of crank journals

- **Technology Evaluation**

- Laboratory bench tests (reciprocating tests)
- Motored single cylinder friction tests
- Motored multi-cylinder friction and wear tests
- Motored engine friction tests
- Fired single cylinder friction tests
- Chassis roll dynamometer tests

Milestone

| | | 2015 | | | | 2016 | | | | 2017 | | | | 2018 | | | | Status |
|--|--|---|---|---|----|---|--|--|----|------|----|---|---|---|----|----|----------|----------|
| | | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | |
| Budget Period I | Develop PTWA Coating Deposition Method |  | | | | | | | | | | | | | | | | Complete |
| | Complete PTWA Coating Characterization | |  | | | | | | | | | | | | | | | Complete |
| | Complete Initial Nanocomposite Charact. |  | | | | | | | | | | | | | | | | Complete |
| | Deliver Initial Assessment of Friction Reduction Potential | | |  | | | | | | | | | | | | | | Complete |
| | Deliver High Porosity PTWA Coating | Go/No-Go | | | |  | | | | | | | | | | | | Go |
| | Budget Period II | Complete Friction Assessment of PTWA Cylinder Bore, Ring, and Piston Coatings | | | | | |  | | | | | | | | | | |
| Complete Lab Bench Test Fric Assessment | | | | | | |  | | | | | | | | | | | |
| Deliver Initial Wear Assessment on PTWA Coatings | | | | | | |  | | | | | | | | | | | |
| Quantify Friction Benefits of Micro-polishing | | | | | | |  | | | | | | | | | | Complete | |
| Demonstrate Engine Component Friction Reduction | | | | | | | Go/No-Go | | | | | |  | | | | | |
| Budget Period III | | Demonstrate Friction Benefits – Single Cylinder Engine | | | | | | | | | |  | | | | | | |
| | Demonstrate Friction Benefits – Full Motored Engine | | | | | | | | | | | | |  | | | | |
| | Demonstrate Friction Benefits – Vehicle | | | | | | | | | | | | |  | | | | |
| | Demonstrate Fuel Economy Benefit | | | | | | | | | | | | |  | | | | |

Technical Accomplishments and Progress

Key Deposition Conditions for High Porosity Plasma Transfer Wire Arc Coatings

Coating Deposition Conditions

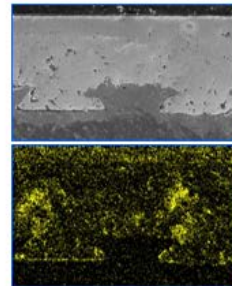
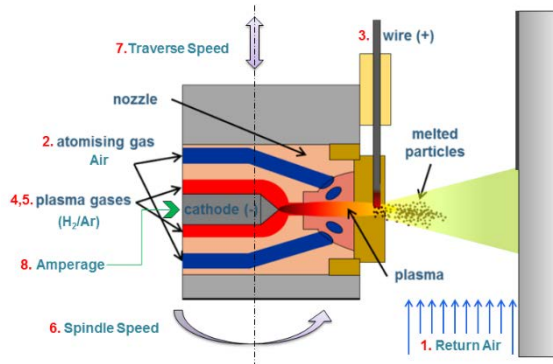
- Electrical Current
- Wire Material and Feed Rate
- Atomizing Gas Pressure and Type
- Plasma Gas Flow Rate
- Torch Design

Coating Characterization

- Porosity, Cross Section and Honed Surface
- Oxide Content
- Hardness
- SEM/EDX, Material Composition
- Microstructure

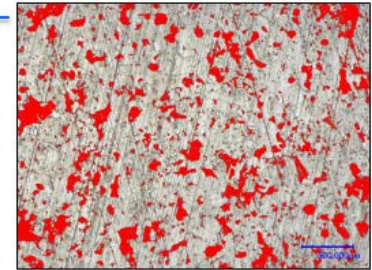
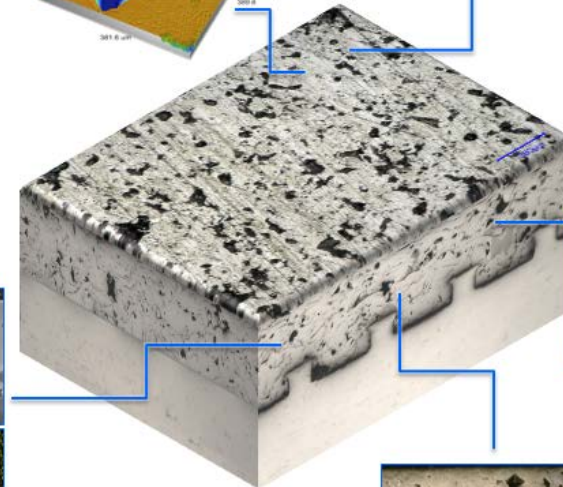
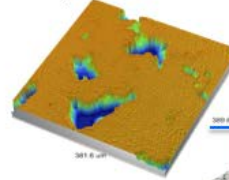
Tests and Analysis

Porosity
Oxide Content
Hardness
SEM/EDX
Microstructure

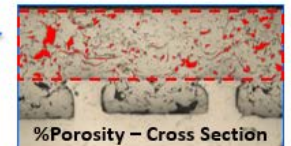


Material Composition –
Cross Section and
Honed Surface

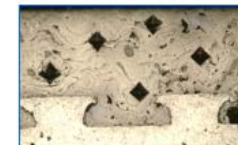
3D profile– Honed Surface



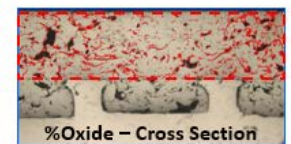
%Porosity – Honed Surface



%Porosity – Cross Section



Hardness – Cross Section and
Honed Surface



%Oxide – Cross Section

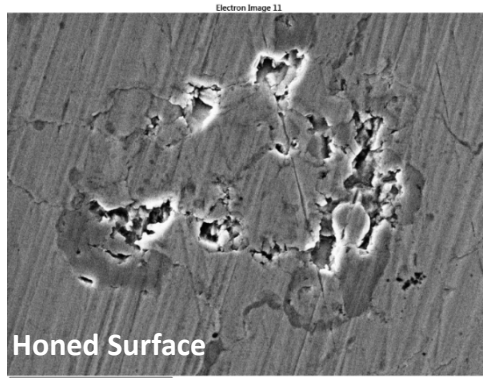
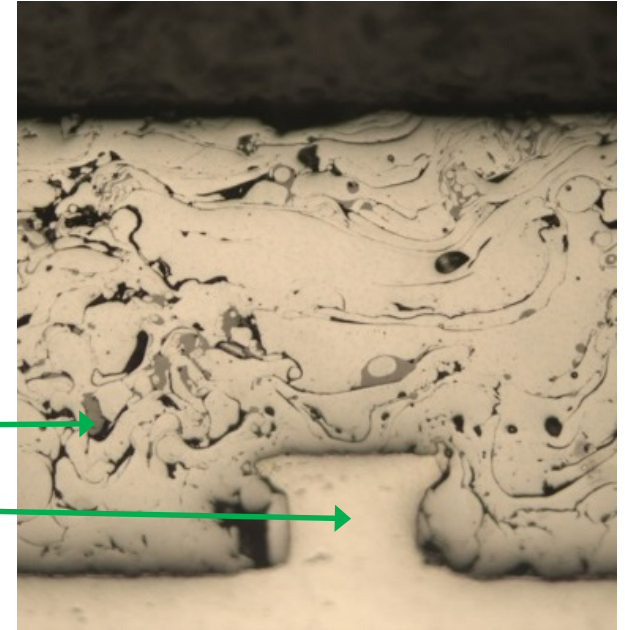
Technical Accomplishments and Progress

High Porosity Plasma Transfer Wire Arc Coatings

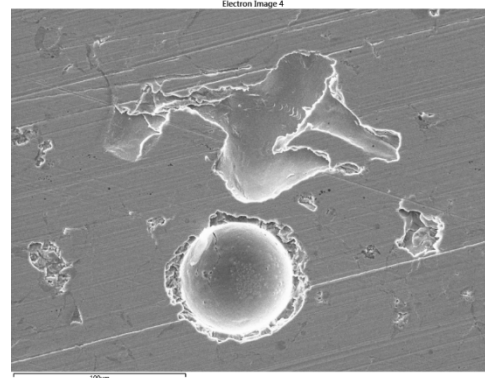
A smooth finish is required to ensure exposing pores

- The pores are created by the Pull-out mechanism.
- Different pull-out pores:
 - Particle pull-outs
 - Delamination or interlayer pull-outs

Oxides
Surface Prep

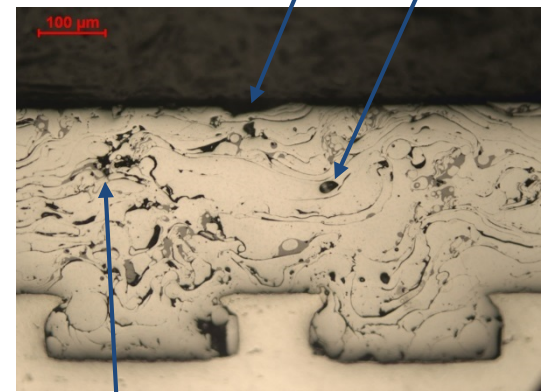


Coating's Natural Porosity exposed by smooth hone



Particle Pull-out Pore

Particle Pull-out Pore
Delamination Pull-out Pore



Coating's Natural Porosity

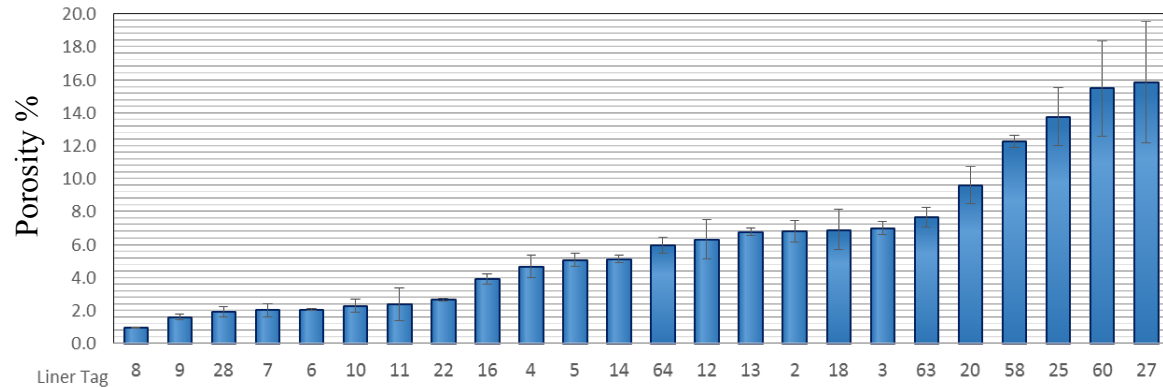
Technical Accomplishments and Progress

High Porosity Plasma Transfer Wire Arc Coatings

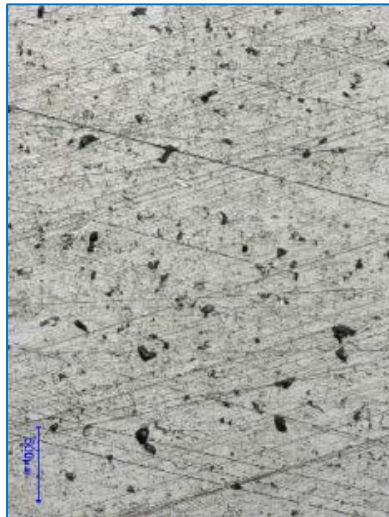
Produce PTWA coating with various levels of porosity

Go/No-Go Decision

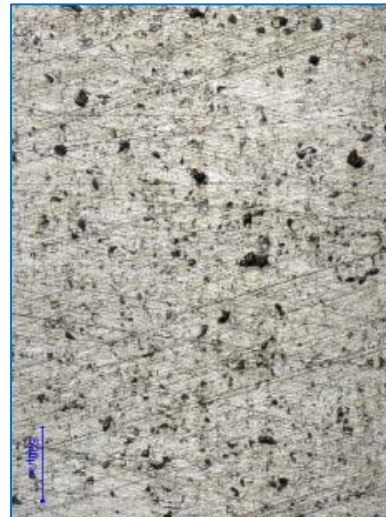
- Low Porosity: %Por < 2
- Mid Porosity: $3 < \%Por < 5$
- High Porosity: $6 < \%Por < 8$



% Porosity – 2.0



% Porosity – 5.1



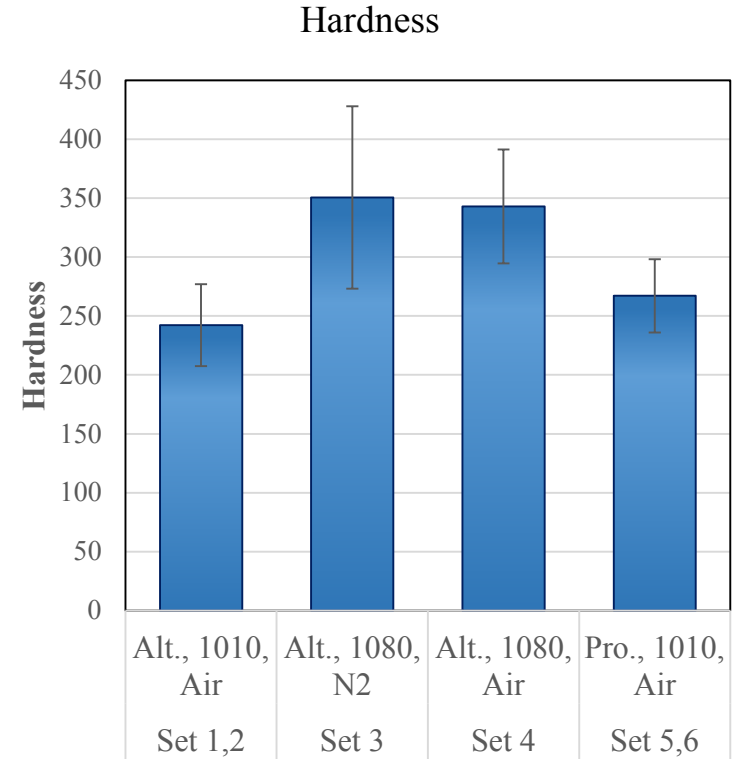
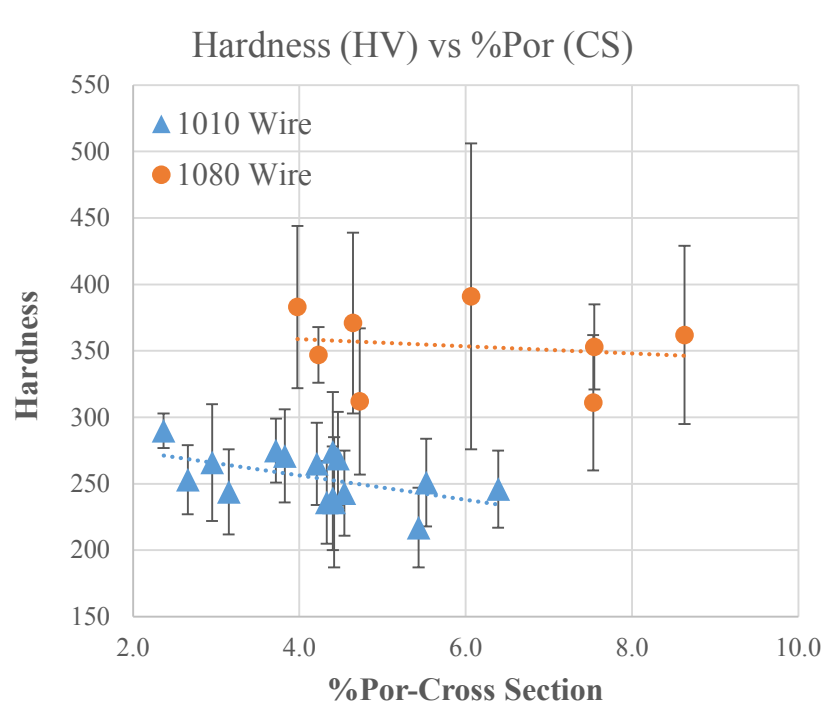
% Porosity – 7.0



% Porosity – 12.2

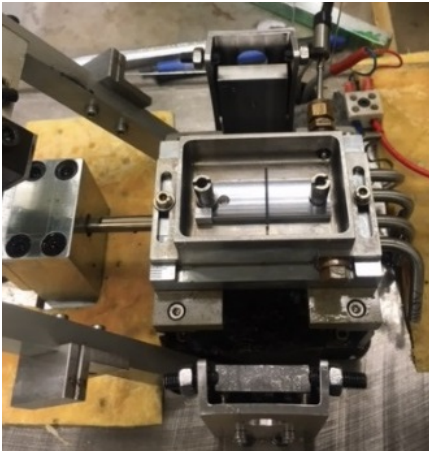
Technical Accomplishments and Progress

High Porosity Plasma Transfer Wire Arc Coatings



Technical Accomplishments and Progress

Plint TE77 friction and wear test on ring segment and liner section

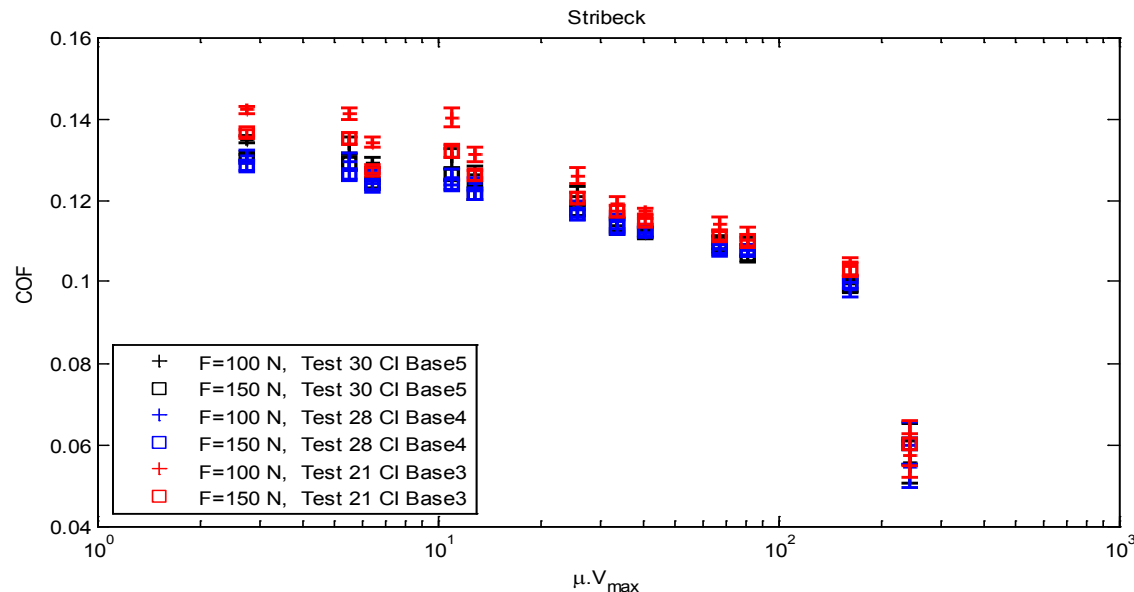


Procedure

- ◆ Run-in before the test and after changing temperature
- ◆ Parameter sweeps:
 - Temp.: 30, 50, 80, 120°C
 - Load: 50, 100, 150N
 - Frequency: 2, 5, 10, 20, 30Hz

Materials

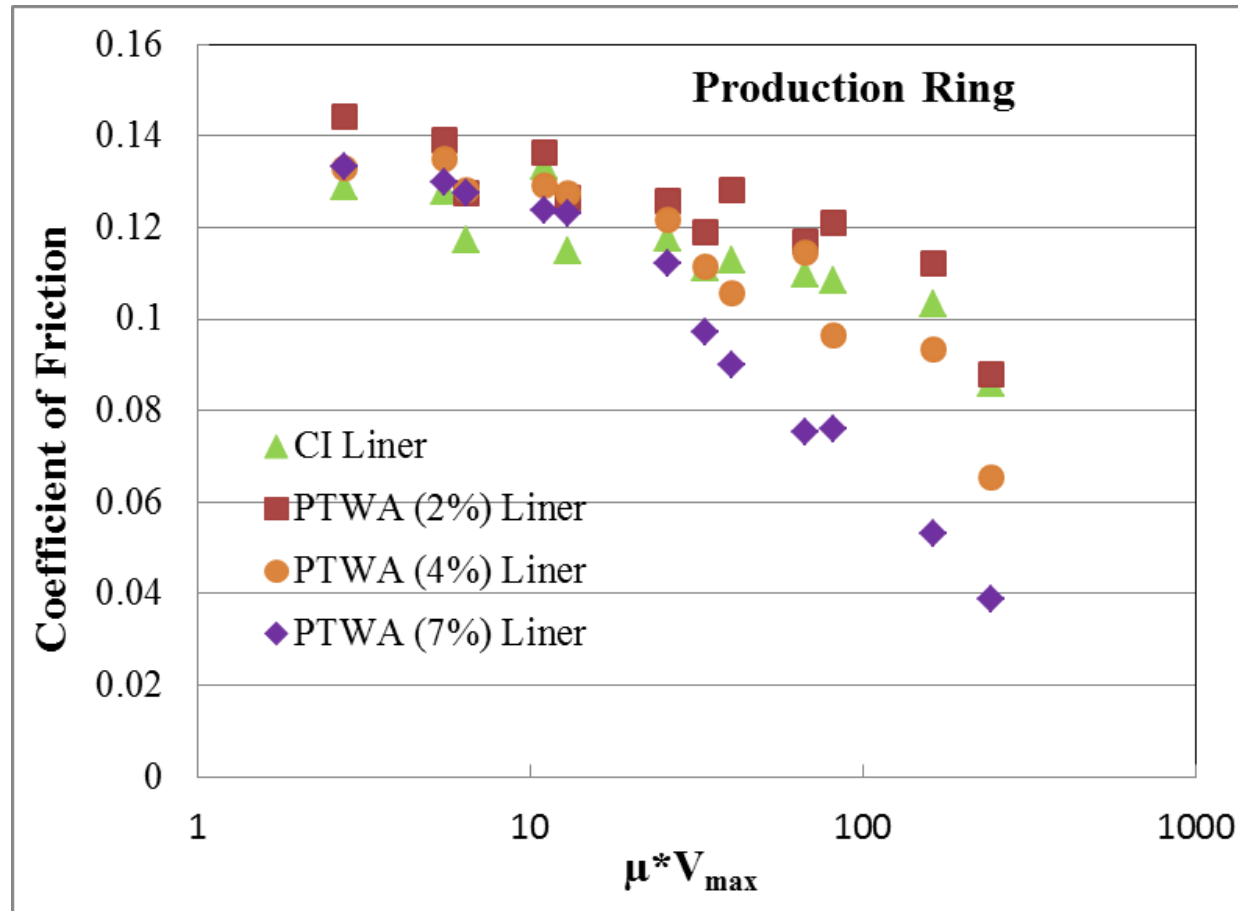
- Liner sections:
 - Production, 92.5mm dia.
- Ring:
 - 87.5 mm dia., production
- Oil:
 - SAE 5W-20 GF-5 oil



The test procedure offers excellent repeatability

Technical Accomplishments and Progress

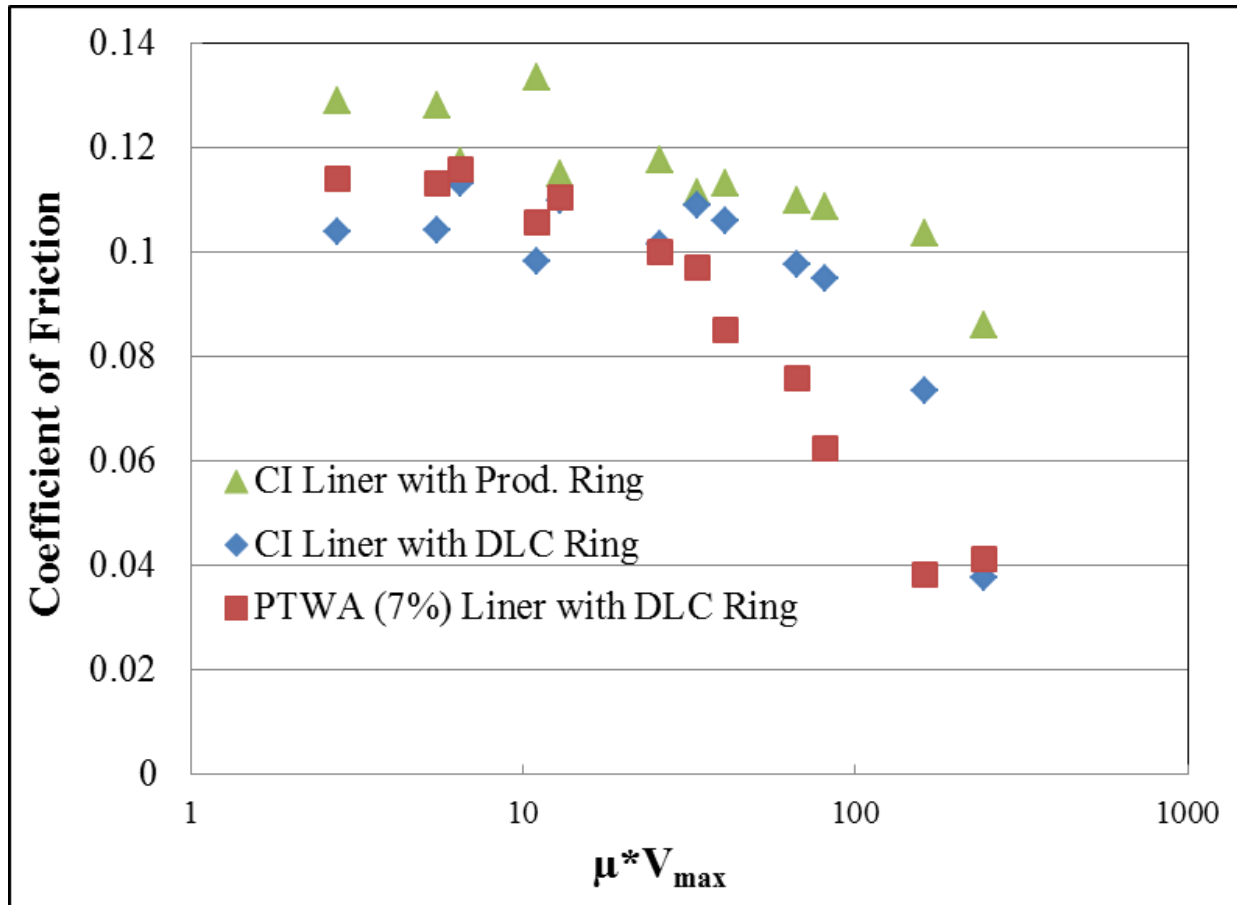
High Porosity Plasma Transfer Wire Arc Coatings



High porosity PTWA coatings offer friction benefit in mixed lubrication regime

Technical Accomplishments and Progress

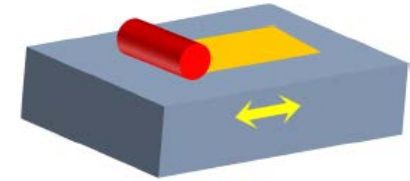
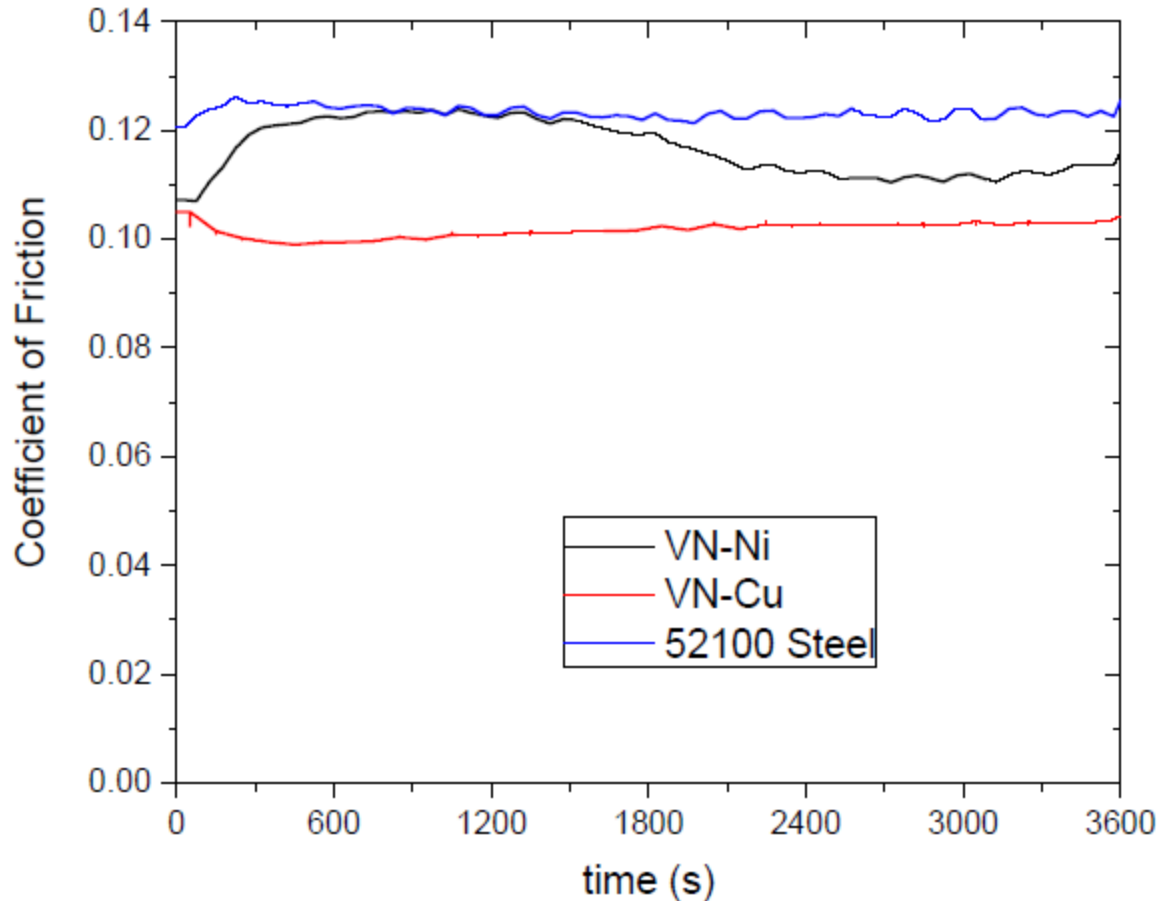
High Porosity Plasma Transfer Wire Arc Coatings



DLC ring offers additional friction benefit

Technical Accomplishments and Progress

Nano-composite Coatings for Piston Rings and Skirts



High Frequency Reciprocating Rig

- Roller and Flat – AISI 52100 steel
- Lubricant – Vehicle aged GF-5 5W-20 oil
- Temp. - 100°C

VN-Cu nano-composite coating showed friction benefit

Technical Accomplishments and Progress

Motored Cranktrain Friction Rig

Objectives

- Demonstrate friction benefits from micro-polished crank journals
- Demonstrate friction benefits from low friction polyalkylene glycol oil

Test Method

- Motored test
- Current production engine hardware
- GF-5 SAE 5W-20 oil (baseline oil)
- Temp.: 40°C, 60°C, 100°C, and 120°C

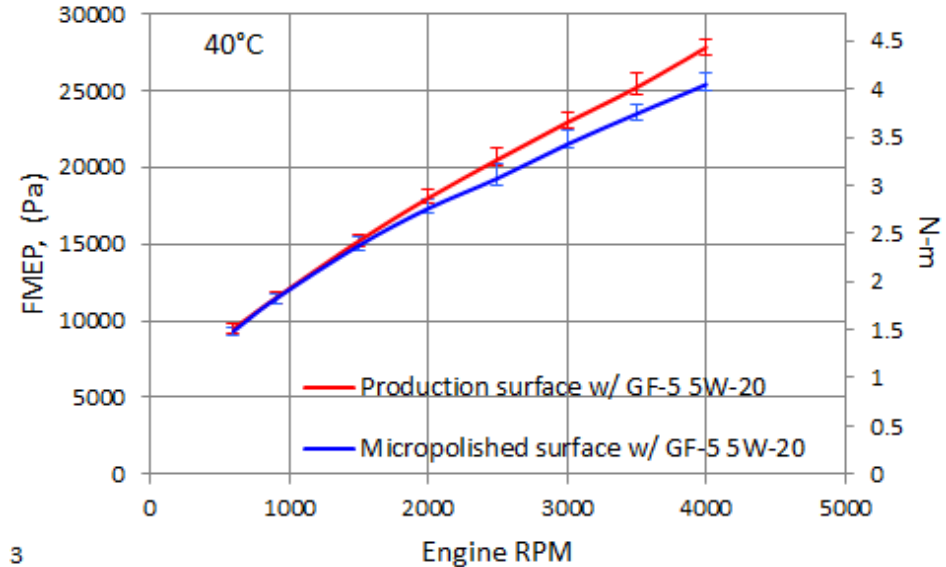
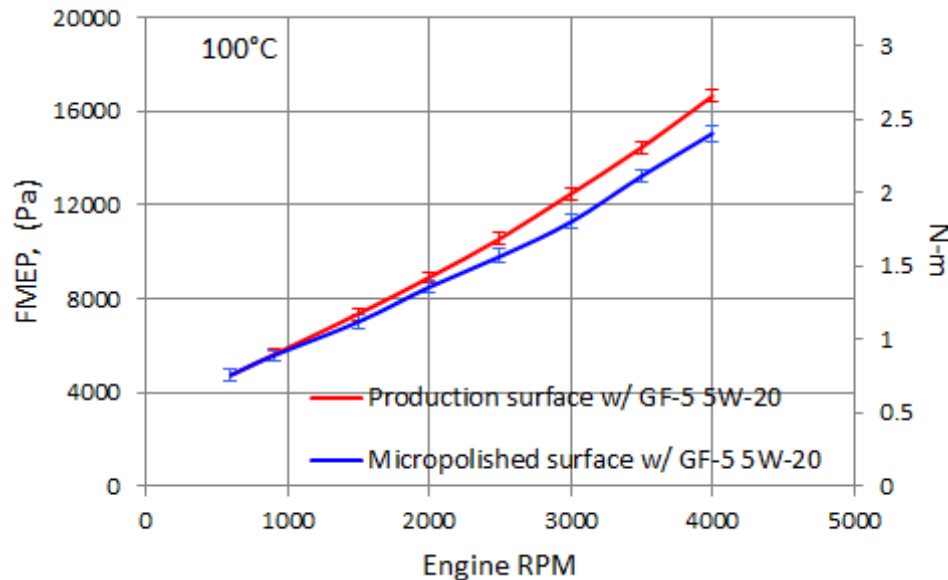


Technical Accomplishments and Progress

Effect of micro-polishing crank main journals

- Only the crank shaft was rotated
- No pistons, con rods

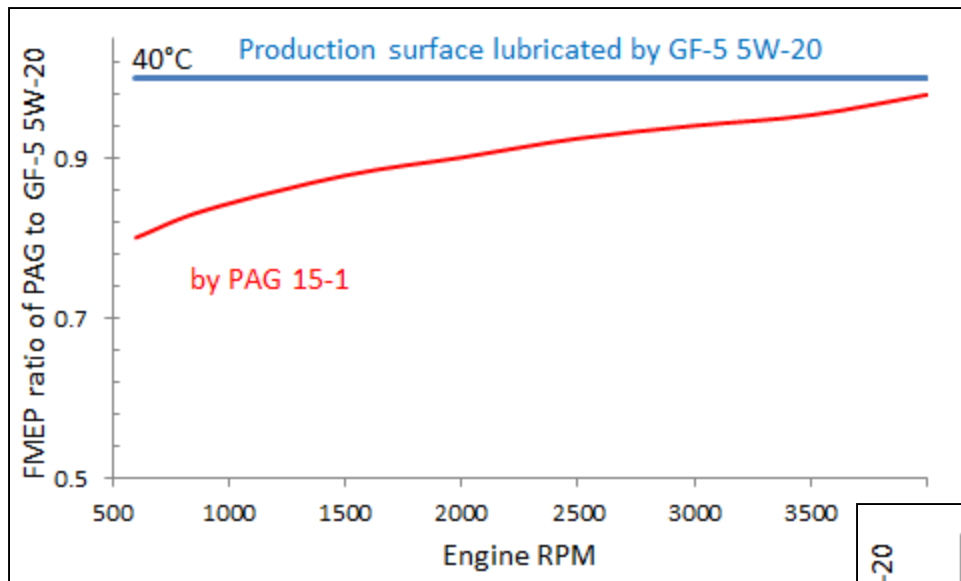
| | Ra | Rq | Rz | Rt |
|-----------------|------|------|------|------|
| Baseline Finish | 0.17 | 0.22 | 1.4 | 1.9 |
| Micro-Polished | 0.05 | 0.07 | 0.58 | 0.69 |



Micro-polished journals showed friction benefit

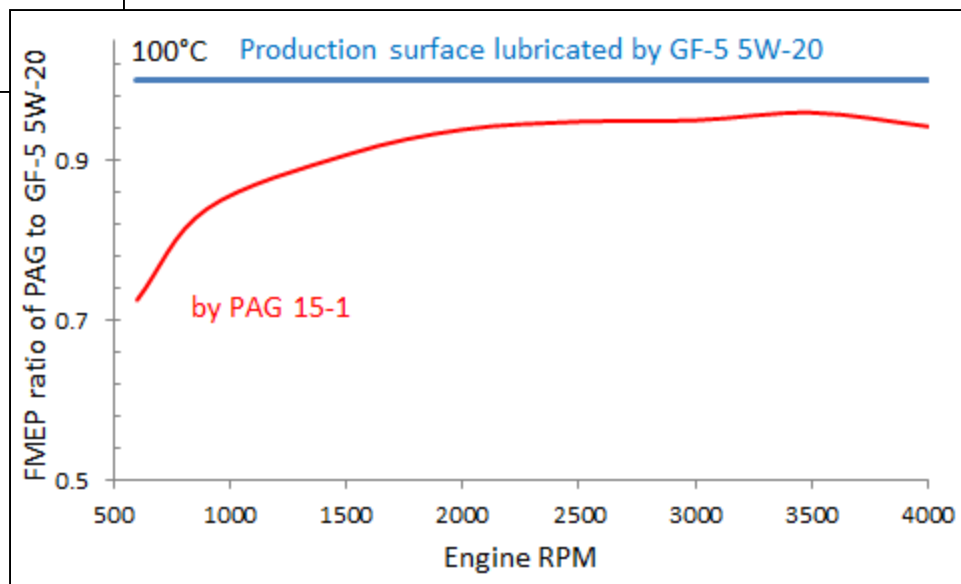
Technical Accomplishments and Progress

Effect of Lubricant Formulation (Polyalkylene Glycol)



| | KV at 40°C (cSt) | KV at 100°C (cSt) |
|----------------|------------------|-------------------|
| GF-5 SAE 5W-20 | 48 | 8.6 |
| PAG 15-1 | 20.3 | 5.5 |

**3-30% friction benefit with
PAG oil depending on
temperature and engine speed**



Coordination and Collaboration with Other Institutions

- **Collaboration – Argonne National Laboratory**
 - Development and deposition of nano-composite coatings (rings and piston skirts)
 - Laboratory friction and wear tests
 - Ball-on-flat tests
 - Ring-liner tests
 - PTWA liner sections, nano-composite coatings
- **Coordination**
 - Comau: Development and deposition of high porosity PTWA coatings
 - Gehring: Development of honing and finishing liners/blocks, CMM inspection
 - Paramount: Mechanical roughening, inspection
 - Mahle: low friction piston rings (Nitrided, PVD, DLC)
 - KS – Pistons for two engines
 - Dow Chemical – Low friction PAG lubricants
 - SwRI – Fired single cylinder tests

Remaining Challenges and Barriers

- Pressurized single cylinder friction test
 - Calibration and test procedure development
- Wear Assessment using radionuclide method
 - Data acquisition system functionality
 - Motored engine rig assembly support
- Engine components delivered on time by suppliers
- Availability of motored engine friction and chassis roll facility support when needed
- Measurable friction benefits observed in component and engine (motored and fired) tests
- Friction benefits observed by individual components may not add up to show total benefit ($2+2 \neq 4$)

Proposed Future Research

Demonstrate

- friction reduction on motored cranktrain rig with PTWA coated blocks (at various porosity levels) – FY 2017 (In-progress) **Go/No-Go Decision point**
- friction reduction on motored cranktrain rig with PTWA coated blocks with low friction rings – FY 2017-18 (ordered rings)
- friction benefits on pressurized single cylinder friction rig
- friction benefits of piston skirt and ring nano-composite coatings against PTWA coated liner in laboratory bench rigs (FY 2017 (in- progress))
- friction benefits on motored full engine tests – FY 2017-18 (planning in progress)
- friction benefits in fired single cylinder engine FY 2017 (hardware preparation In-progress)
- durability (wear) of rings and PTWA coating in a motored cranktrain rig using RTM (FY2017-18)
- chassis roll fuel economy benefit (FY 2018)

Potential Issues and Barriers

- Pressurized single cylinder friction rig may not be fully functional to the desired level – Fall back on multi-cylinder motored and fired single cylinder friction tests
- Maintaining project timeline because of complex coordination with various suppliers

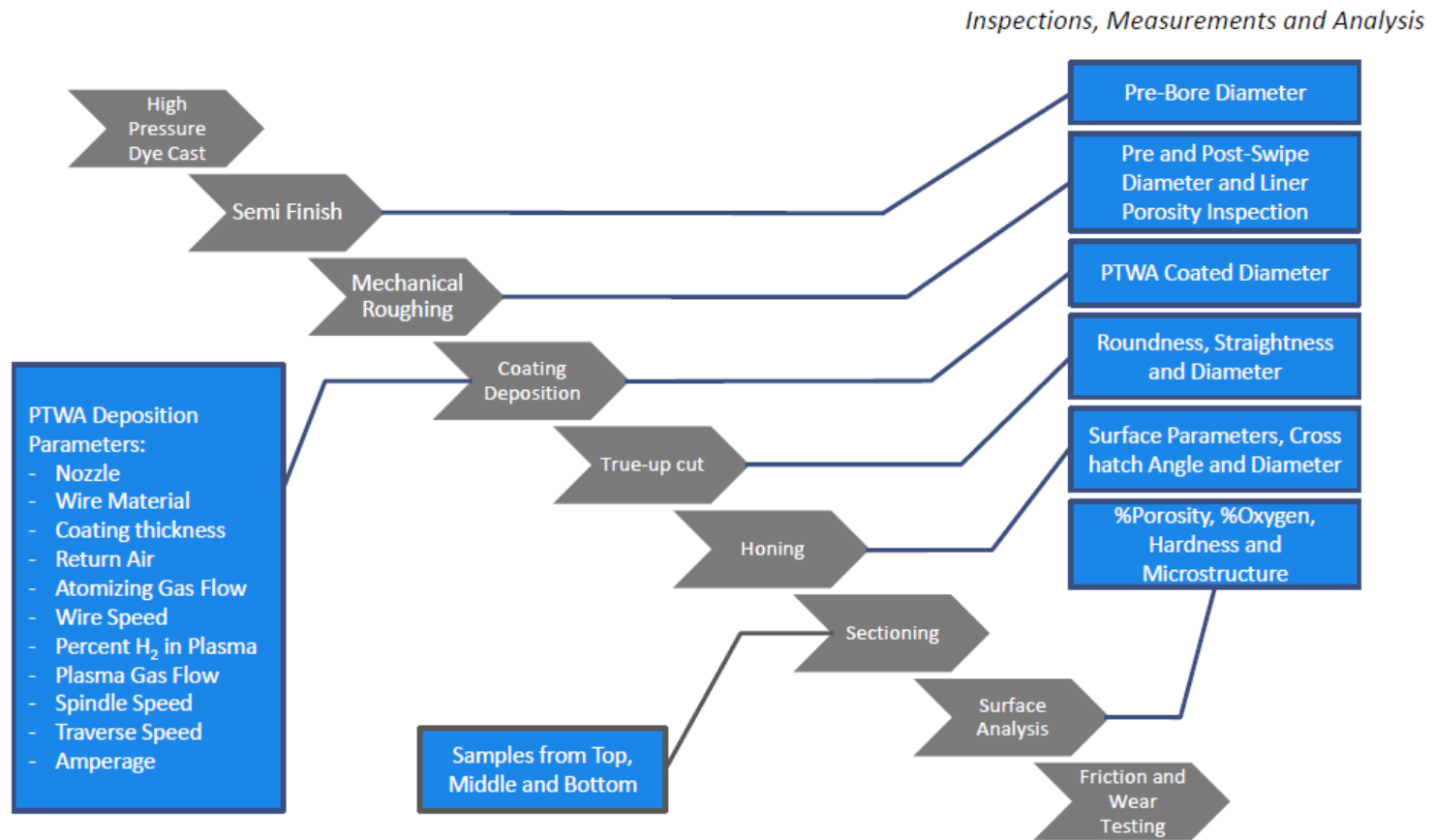
Any proposed future work is subject to change based on funding levels.

Summary

- The work to date has
 - Met (even exceeded) the first Go/No-Go decision point by demonstrating the ability to deposit PTWA coating at three porosity levels
 - Demonstrated friction benefit with high porosity PTWA coatings in lab bench rigs
 - Demonstrated low friction coatings (PVD, DLC) on rings provide additional friction benefit in lab bench rigs
 - Nano-composite VN-Cu coating showed promising friction reduction benefit
 - Demonstrated the effectiveness of micro-polished crank journals in reducing friction
 - Demonstrated the effectiveness of polyalkylene glycol based engine oil in reducing friction

Technical Back-up Slides

Technical Accomplishments and Progress



Achieving consistent coating quality requires multiple steps and complex coordination between various suppliers

Porosity Characterization

Developed different techniques to measure and quantify surface porosity.

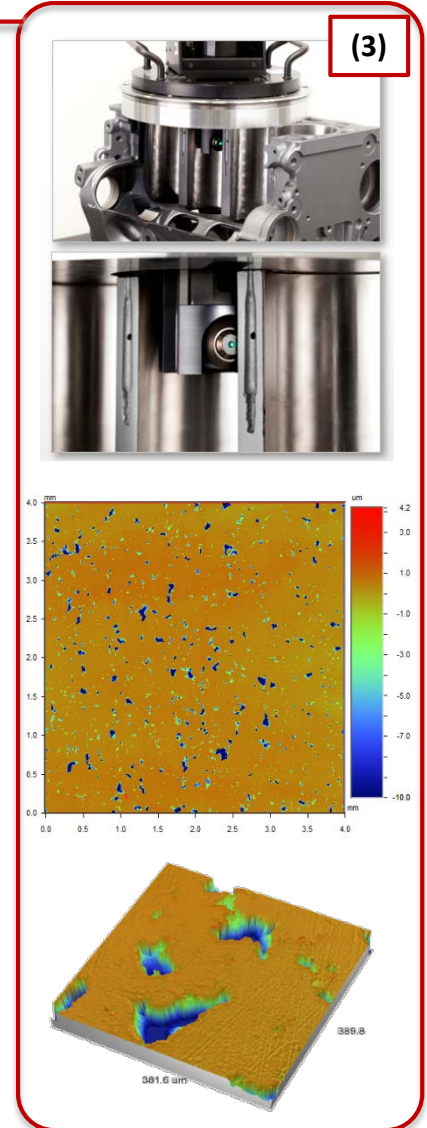
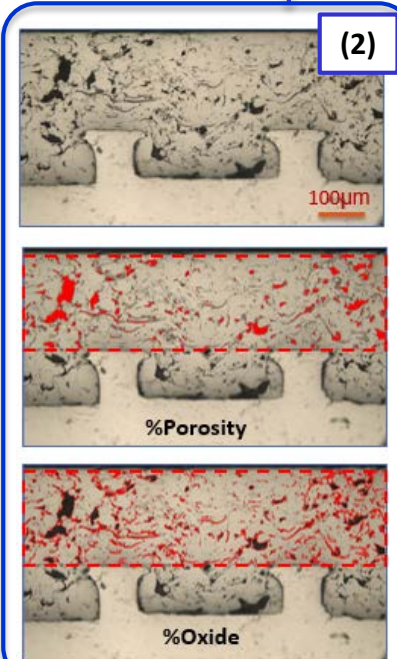
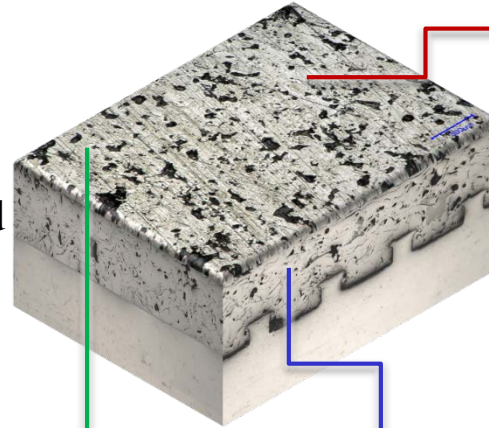
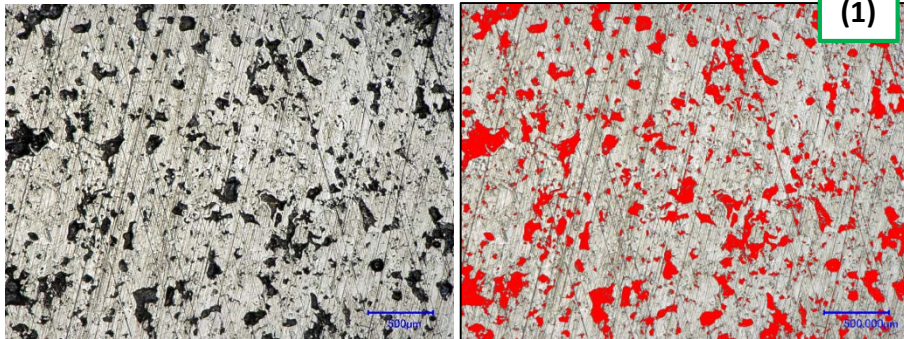
Microscopy Methods (for cylinder liners)

1. Keyence VHX2000 Digital Microscope to measure honed surface porosity.
2. Microphot FXA Optical Microscope and ImagePro to measure cross section porosity and oxide phase.

Profilometry Method (for cylinder blocks)

3. In-bore 3D Optical Profilometer to measure porosity on honed engine blocks.

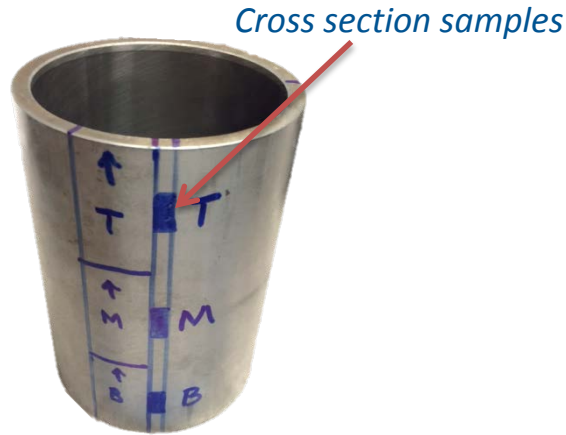
Developed standard porosity samples to tune different methods.



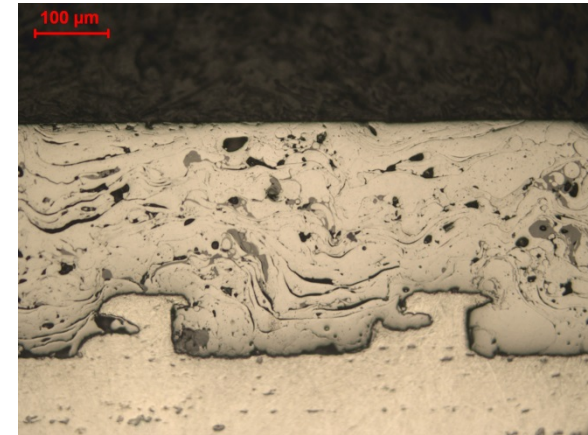
Technical Accomplishments and Progress

High Porosity Plasma Transfer Wire Arc Coatings

Porosity Characterization



Top



\$4

Porosity: 4.31%

Error: $\pm 1.85\%$

Oxide: 10.22%

Error: $\pm 1.89\%$

Hardness:

Error:

Middle

\$4

Porosity: 5.09%

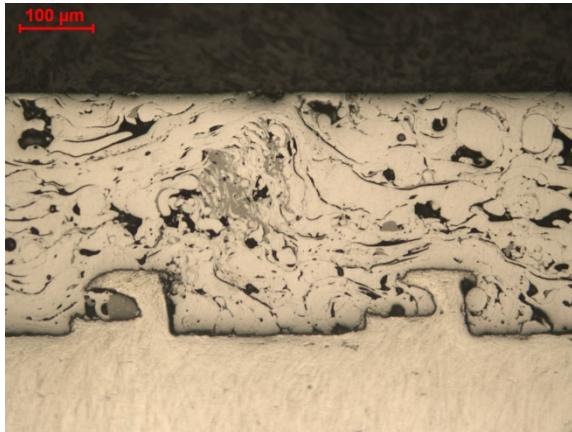
Error: $\pm 1.69\%$

Oxide: 10.36%

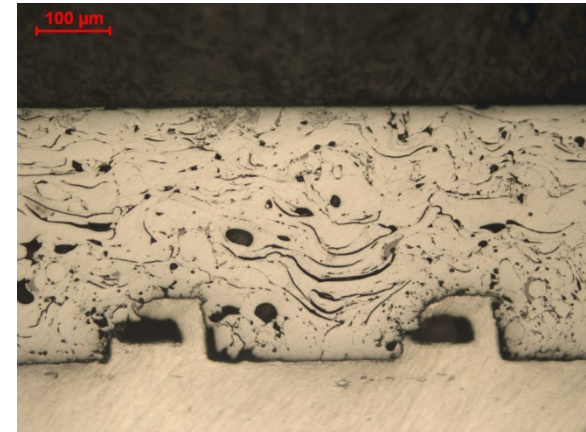
Error: $\pm 1.55\%$

Hardness:

Error:



Bottom



\$4

Porosity: 3.85%

Error: $\pm 0.94\%$

Oxide: 8.51%

Error: $\pm 1.11\%$

Hardness:

Error:

Consistent coating quality across liner stroke